Dark Energy in the Universe

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March 25, 2003

Overview

Evidence for Dark Energy

- Age: Hubble constant $+$ globular clusters
- Distance vs. redshift: Type Ia Supernovae
- Inventory: CMB ($\Omega = 1$) $+$ Many ($\Omega_m \simeq 0.3$)
- Growth function: Weak lensing & Cluster counts

Overview

What is it?

- Cosmological constant Λ: Historical edge (Einstein), very unlikely

- $\Lambda = 0$; transient energy, eventually will go to zero: Modern favorite, very unlikely

Evidence for Dark Energy

Expansion determined by Einstein Equations for scale factor a. If the universe is flat, then

$$H^2 \equiv \underbrace{\left(\frac{da/dt}{a}\right)^2}_{\text{"kinetic energy"}} = \underbrace{\frac{8\pi G}{3}\rho}_{\text{"potential energy"}}$$

and

$$\underbrace{\frac{d^2a}{dt^2}}_{\text{Acceleration}} = \underbrace{-\frac{4\pi G\rho a}{3}\left(1 + \overbrace{3w}^{\text{new term}}\right)}_{\text{Force per mass}}$$

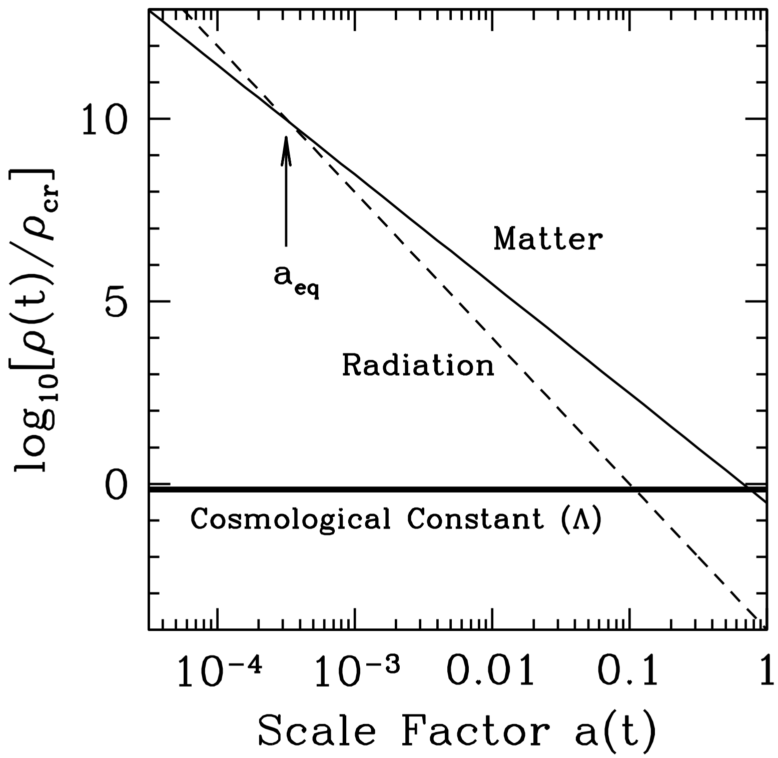
with $w \equiv P/\rho$.

Decceleration unless $w < 0$.

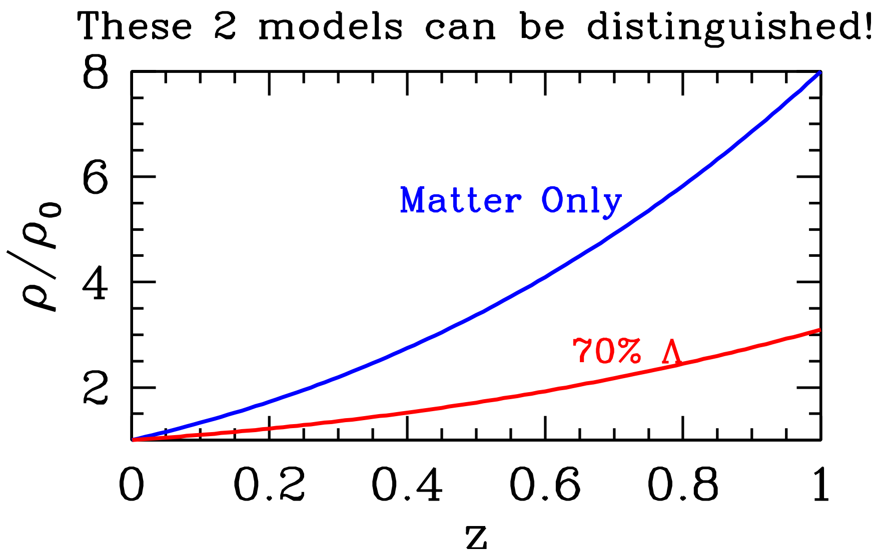
Evidence for Dark Energy

$$\rho \propto a^{3(1+w)} = (1+z)^{-3(1+w)}$$

- Matter density scales as a^{-3} ($w = 0$)
- Radiation scales as a^{-4} ($w = 1/3$)
- Cosmological constant is ... constant ($w = -1$)



Evidence for Dark Energy



Expansion rate was slower in Λ model ↔ The universe is accelerating!

Evidence for Dark Energy

What observables depend on $H(z)$?

- Age of the universe: $t = \int_0^\infty \frac{dz}{H(z)(1+z)}$.

- Luminosity distance:

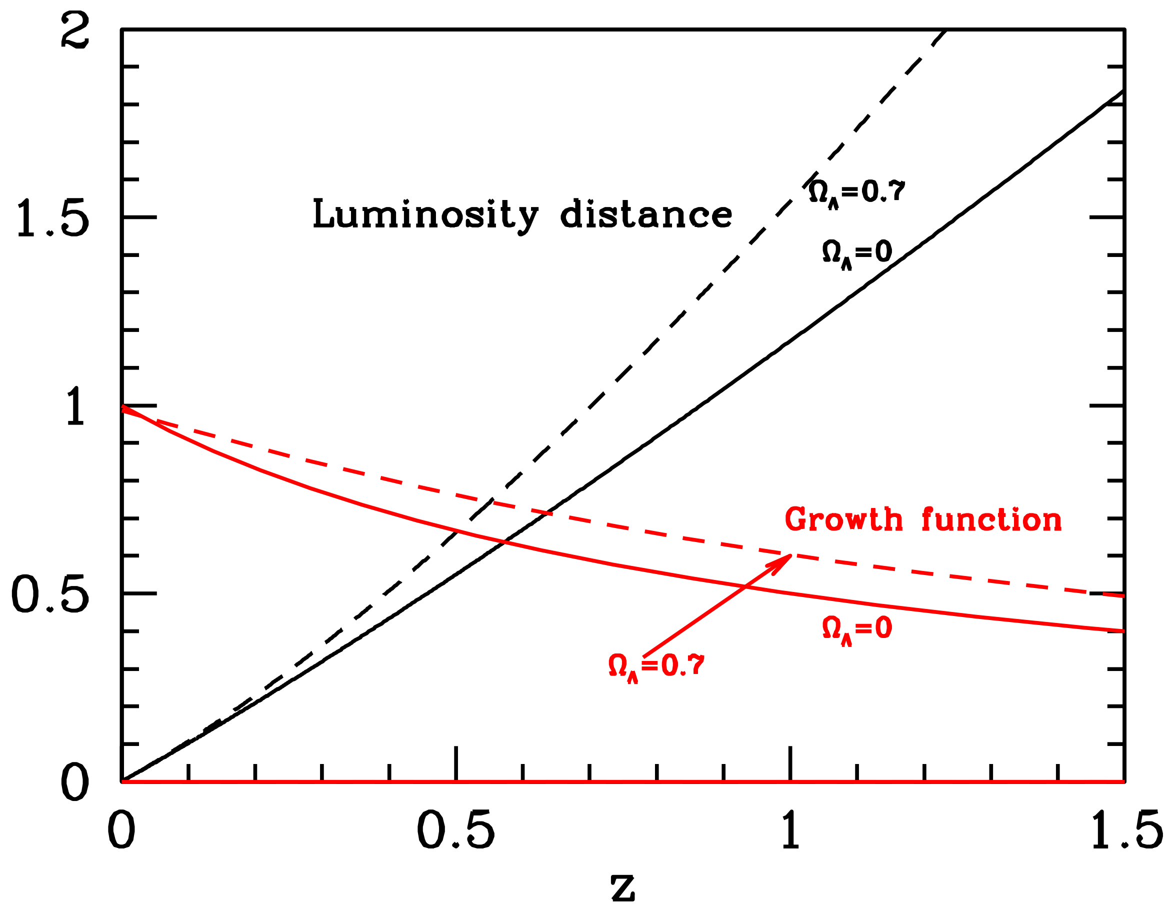
$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

- Angular diameter distance to recombination: $d_* = \frac{1}{1+z_*}\int_0^{z_*} \frac{dz}{H(z)}$

- Growth function:

$$D_1(z) = \frac{5\Omega_m}{2}\frac{H(z)}{H_0}\int_0^z \frac{dz'\,(1+z')}{(H(z')/H_0)^3}$$

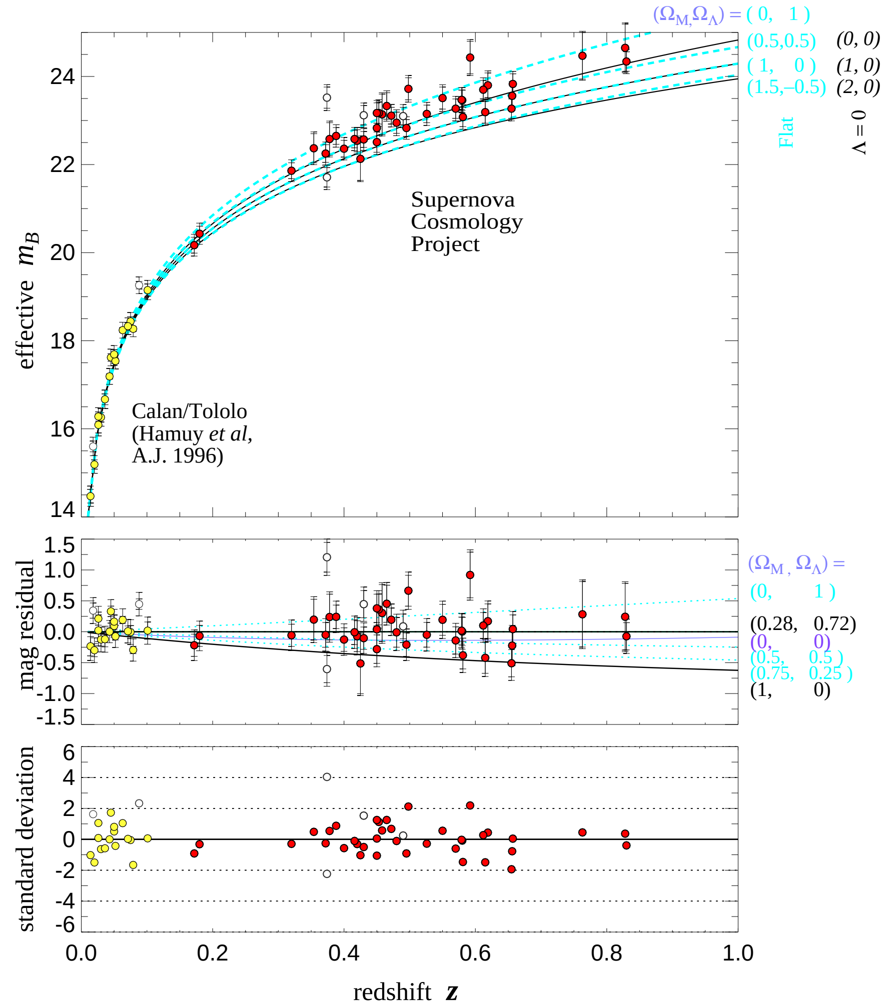
Evidence for Dark Energy



Evidence for Dark Energy: d_L

Type Ia Supernovae

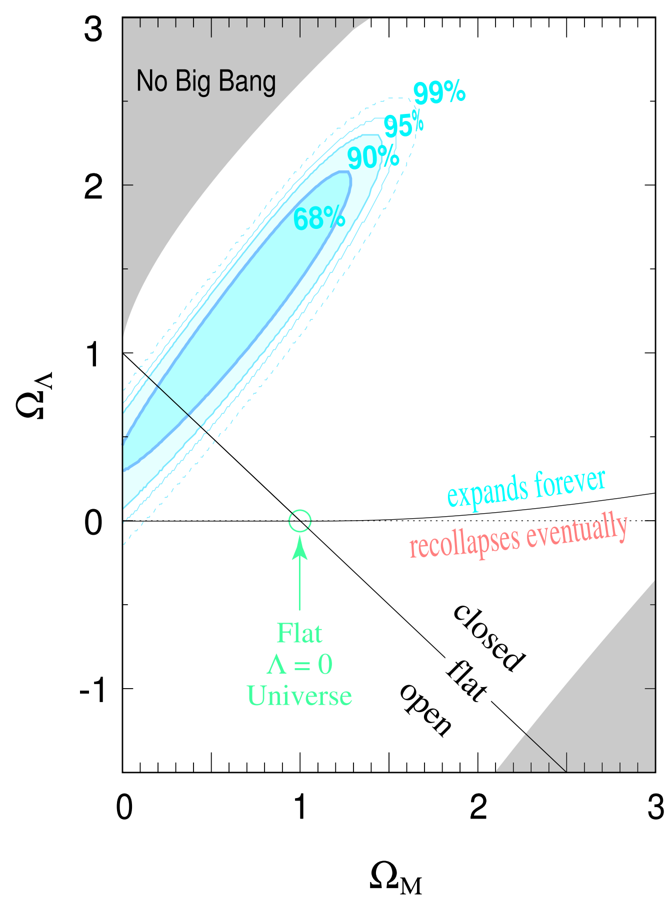
- Observed flux proportional to L/d_L^2. Type Ia SN are *standard candles* (identical L), so their apparent magnitude is a measure of d_L
- $H(z)$ smaller in Λ model $\longrightarrow$ d_L larger $\longrightarrow$ fainter SN



Perlmutter, *et al.* (1998)

Evidence for Dark Energy: d_L

$>$ 50 SN observed by 2 teams imply $\Omega_\Lambda \neq 0$.

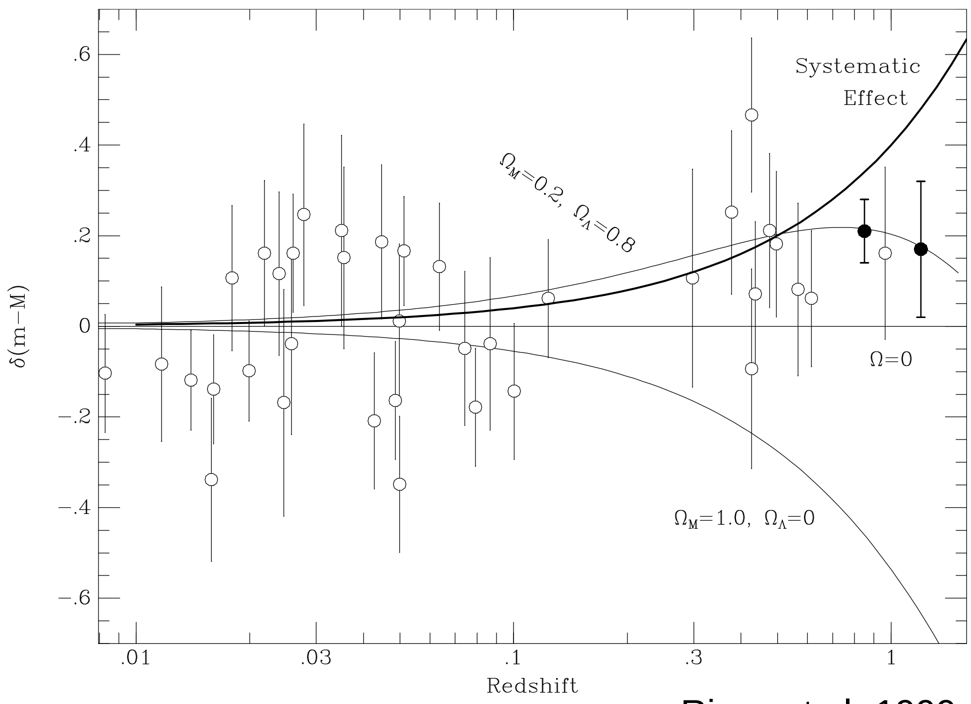


Riess et al. 1999

Evidence for Dark Energy: d_L

Systematic Effect?

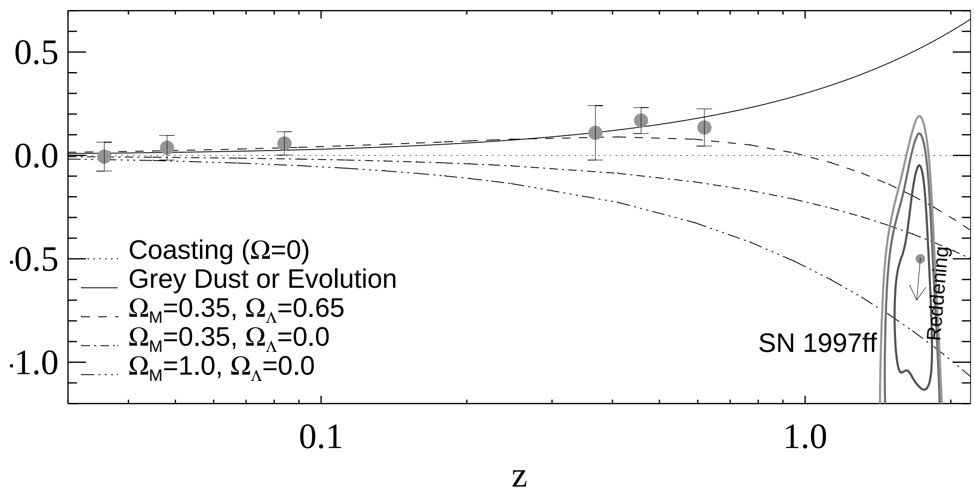
Ordinary dust *reddens* the image; this is not seen. Gray dust leads to lower fluxes as z increases



Riess et al. 1999

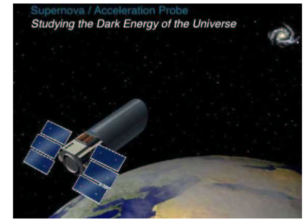
Evidence for Dark Energy: d_L

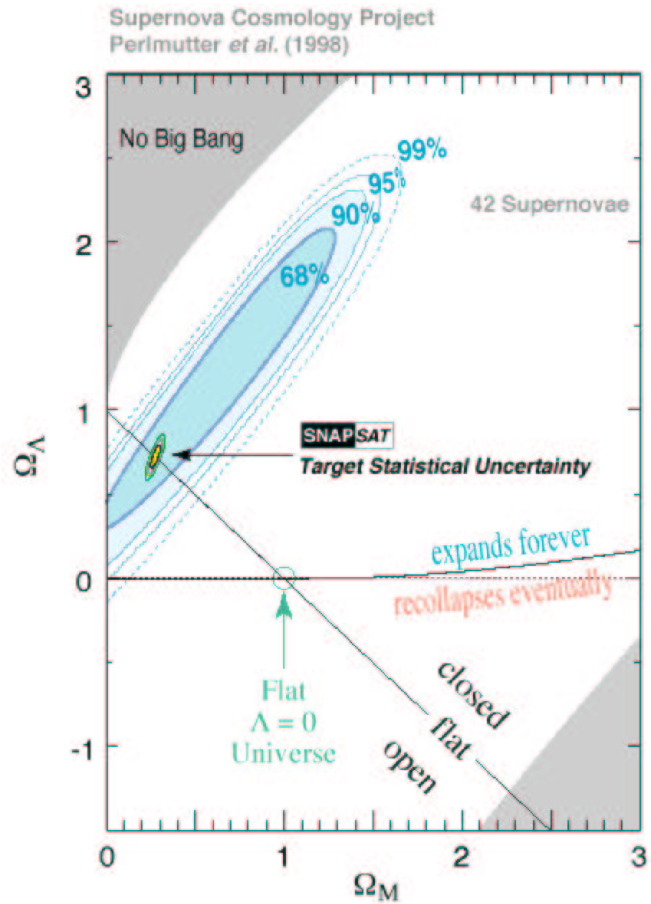
Recently SN observed at $z = 1.7$



Riess et al. 2001

Evidence for Dark Energy: d_L





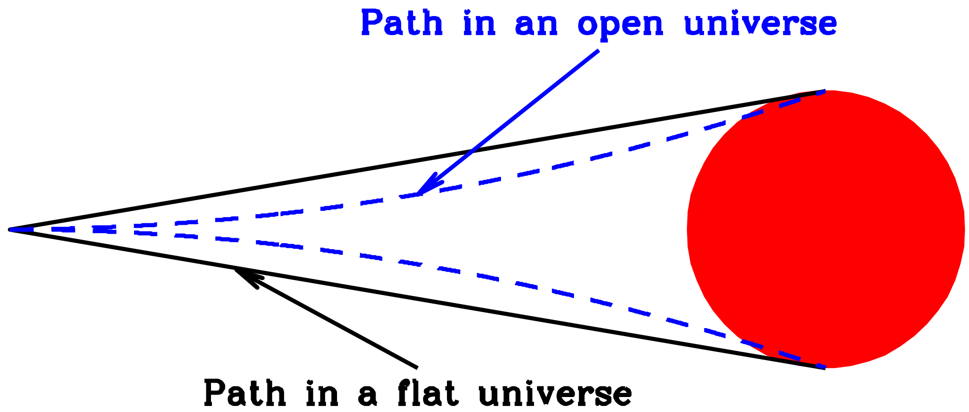
Proposed mission SNAP will observe thousands of distant SN at $z \simeq 1$

Evidence for Dark Energy: Inventory

- Hot/cold spots in CMB at $z = 1100$ are the size of sound horizon. Apparent size depends on geometry of universe.

- There are many estimates of matter density: all yield $\Omega_m = 0.3$.

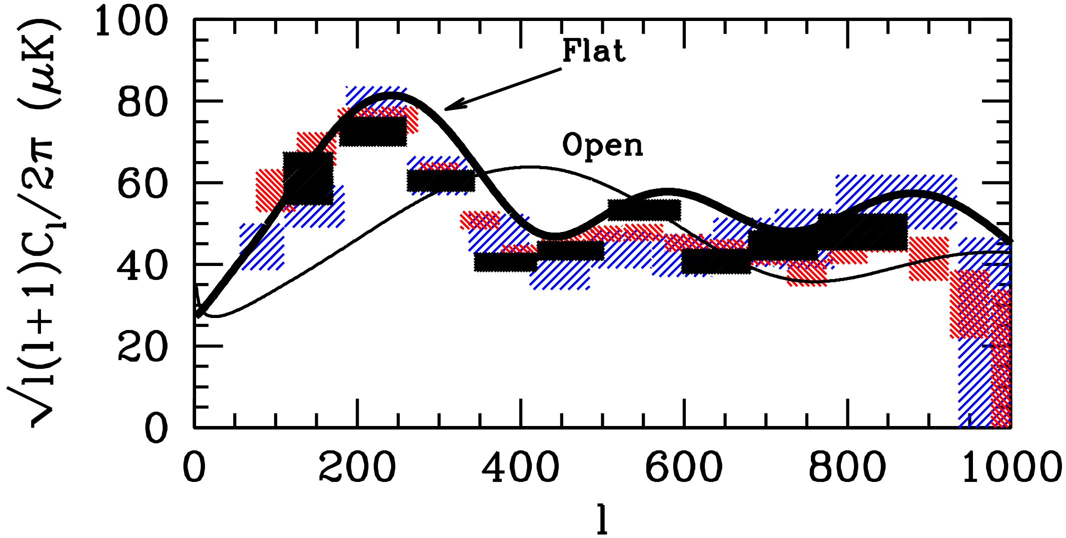
Evidence for Dark Energy: CMB



Angular size of hot/cold spots distinguishes between open, closed or flat universe.

Evidence for Dark Energy: CMB

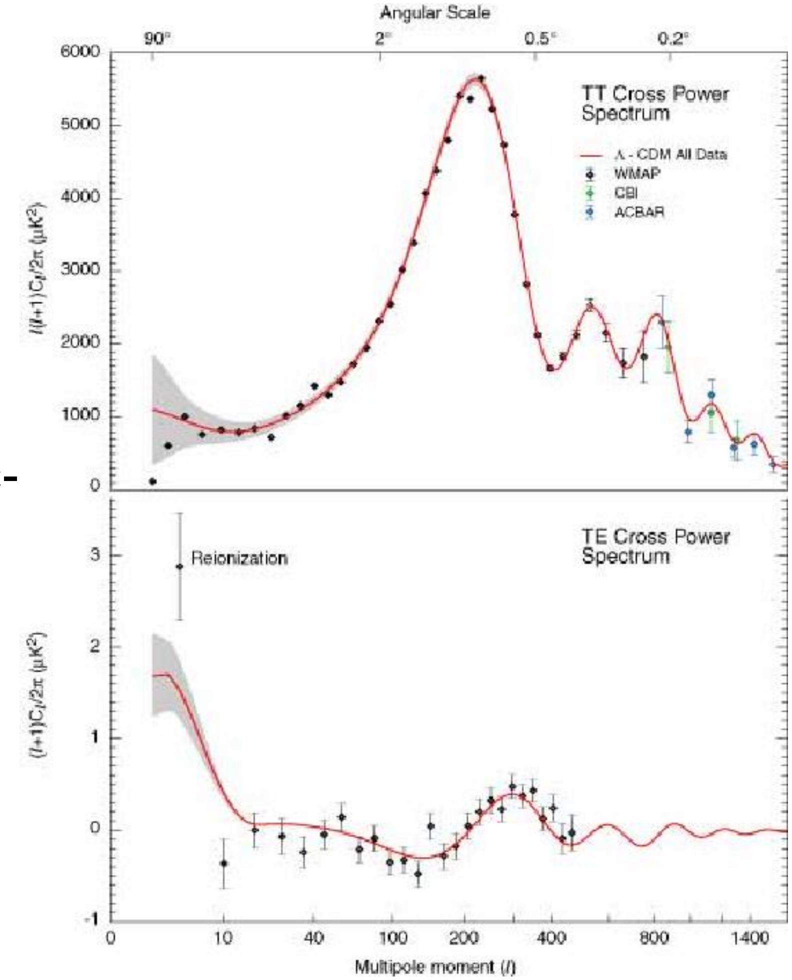
Boomerang
DASI
Maxima
TOCO
CBI
Python
MSAM
Viper VSA
QMAP



Prior to 2003, ~ 10 experiments have verified position of first peak. Our universe is flat $\longrightarrow$ Total energy density is equal to the critical density.

Evidence for Dark Energy: CMB

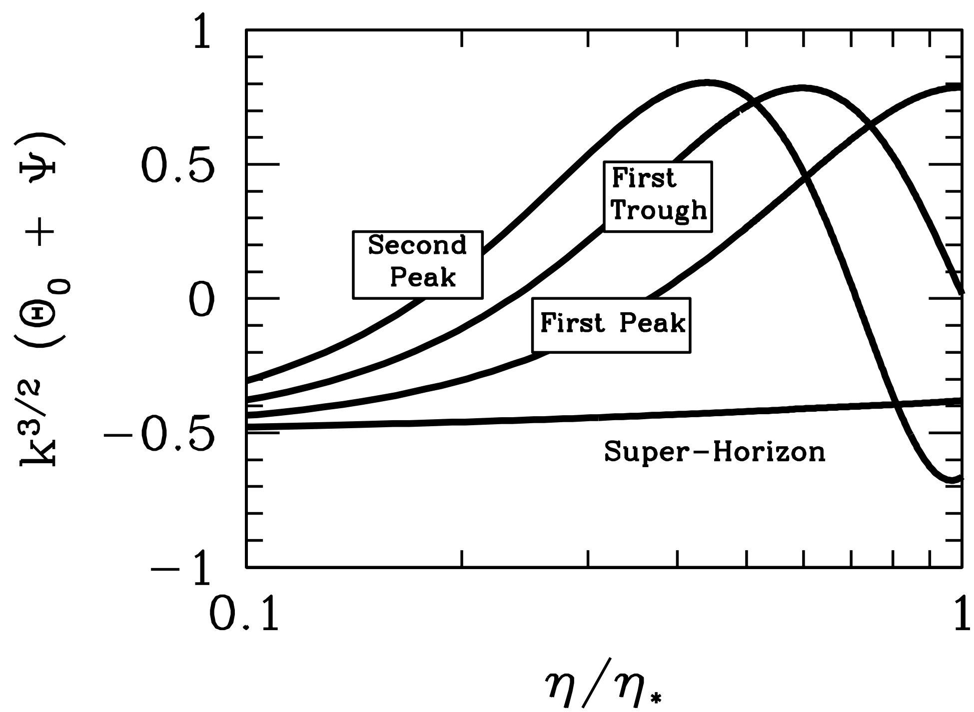
Now WMAP has measured the spectrum with exquisite precision



Bennett et al. 2003

Evidence for Dark Energy: CMB

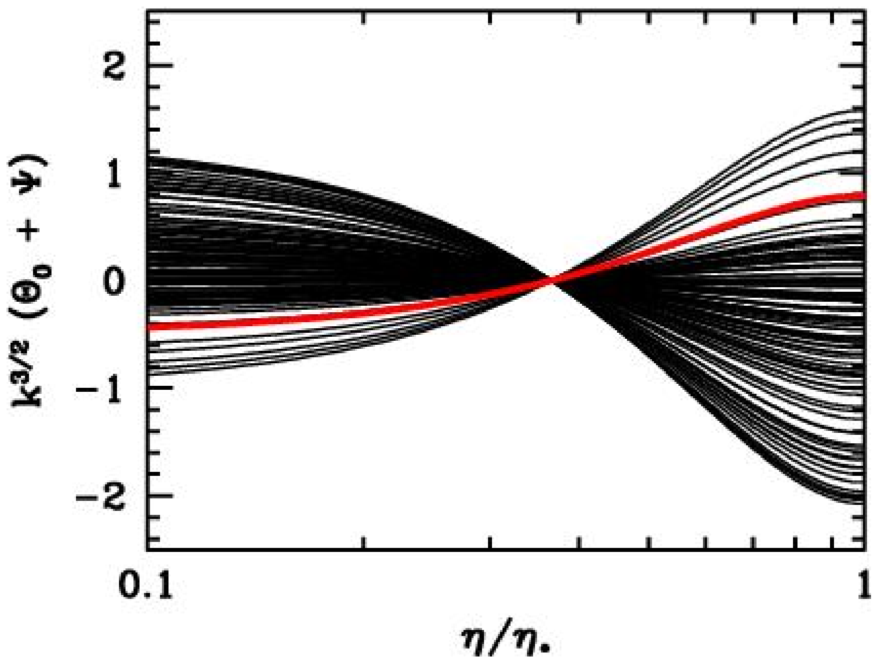
- Small scale modes enter horizon earlier; have undergone more oscillations.
- Observers today seee mode amplitude at recombination (η_*)



Time $\longrightarrow$

Evidence for Dark Energy: CMB

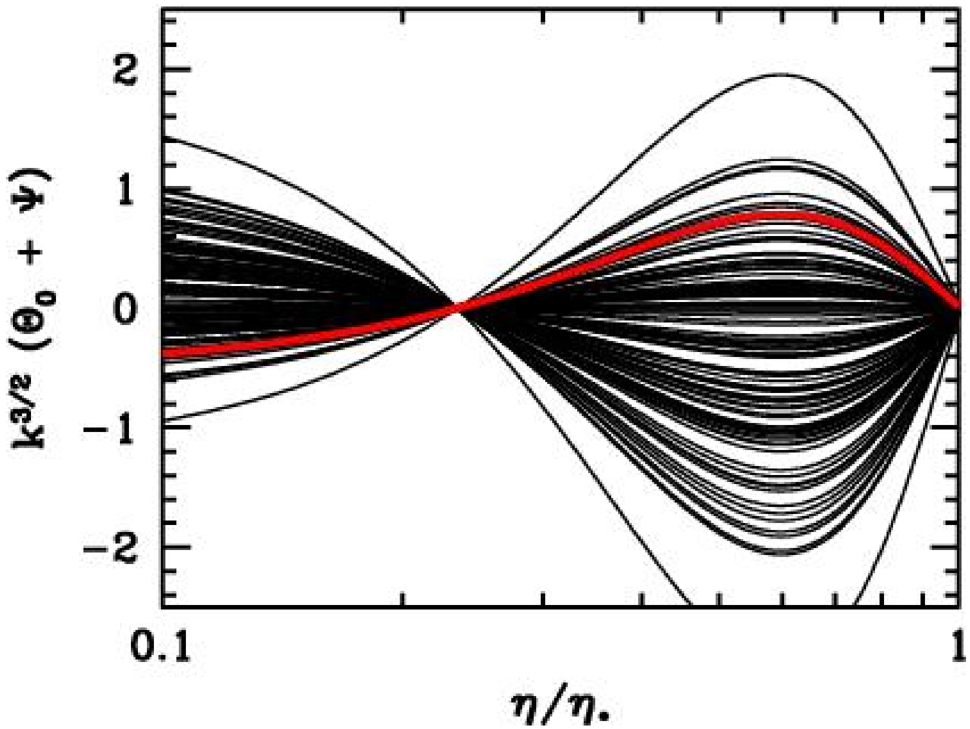
- There are many wavevectors $\vec{k}$ which contribute to anisotropies on fixed angular scale
- Their amplitudes vary, but their phases (all start with constant δT: cosine mode) are fixed
- *First peak* mode has large dispersion at re-combination



Time $\longrightarrow$

Evidence for Dark Energy: CMB

First trough mode has small dispersion at re-combination

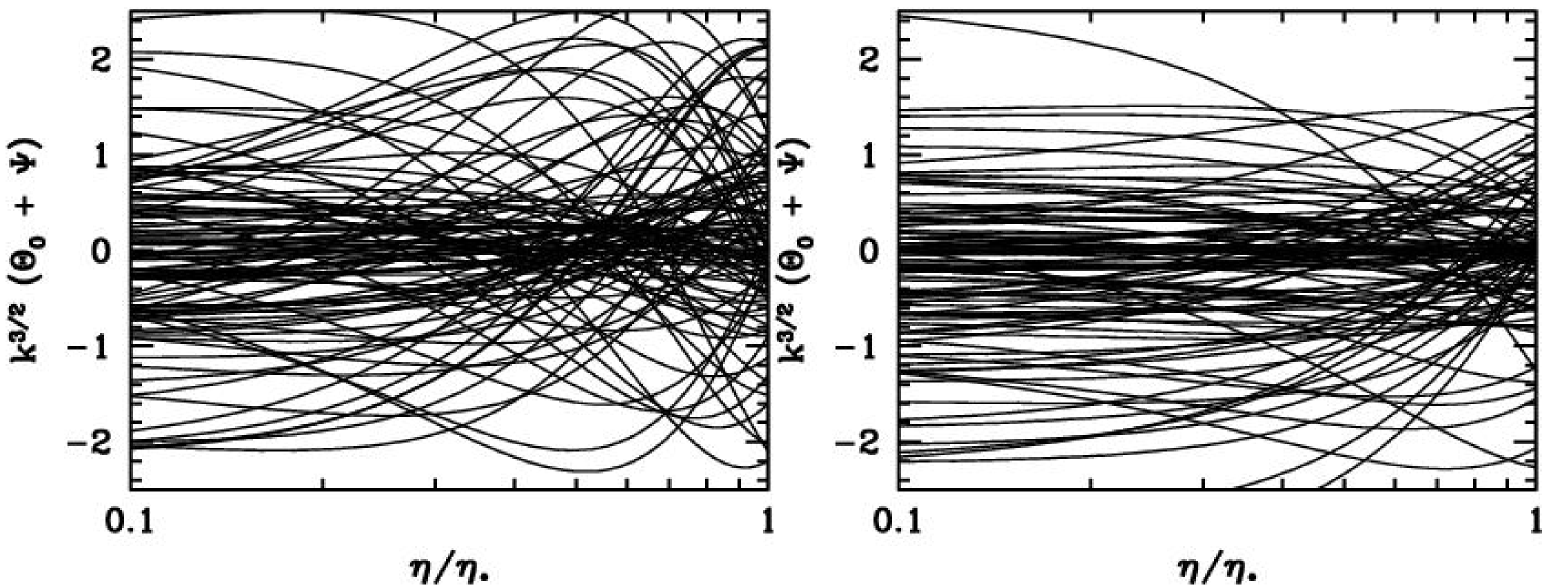


Time $\longrightarrow$

Evidence for Dark Energy: CMB

With random phases ...

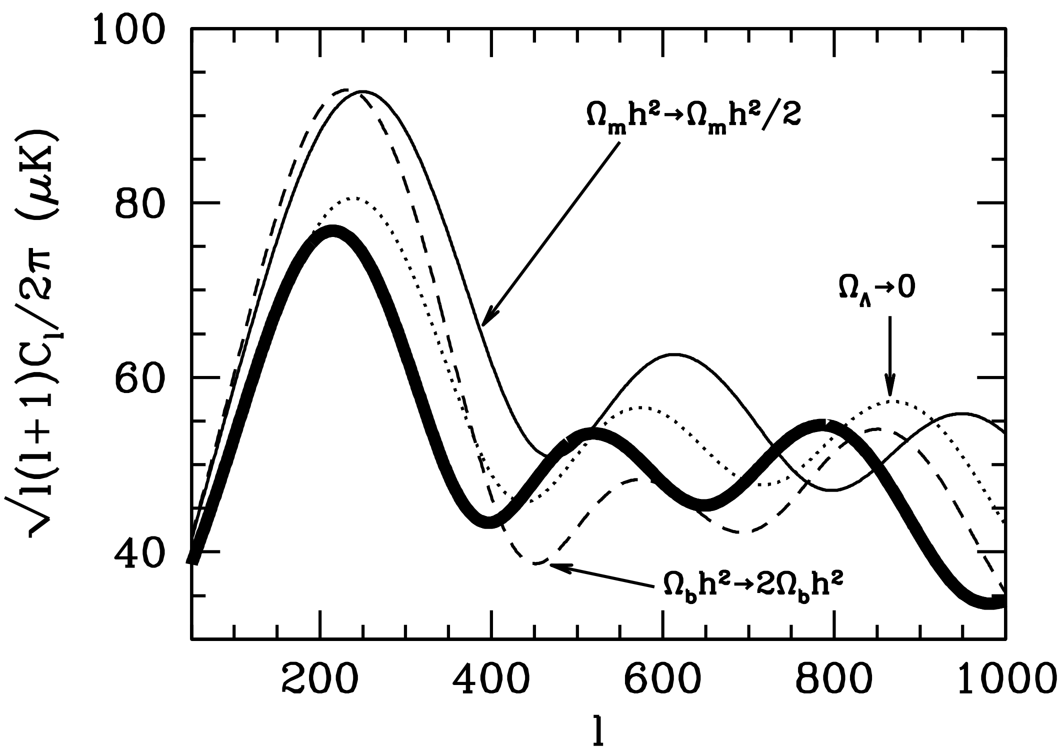
"First peak" "First trough"



Inflation sets the phases

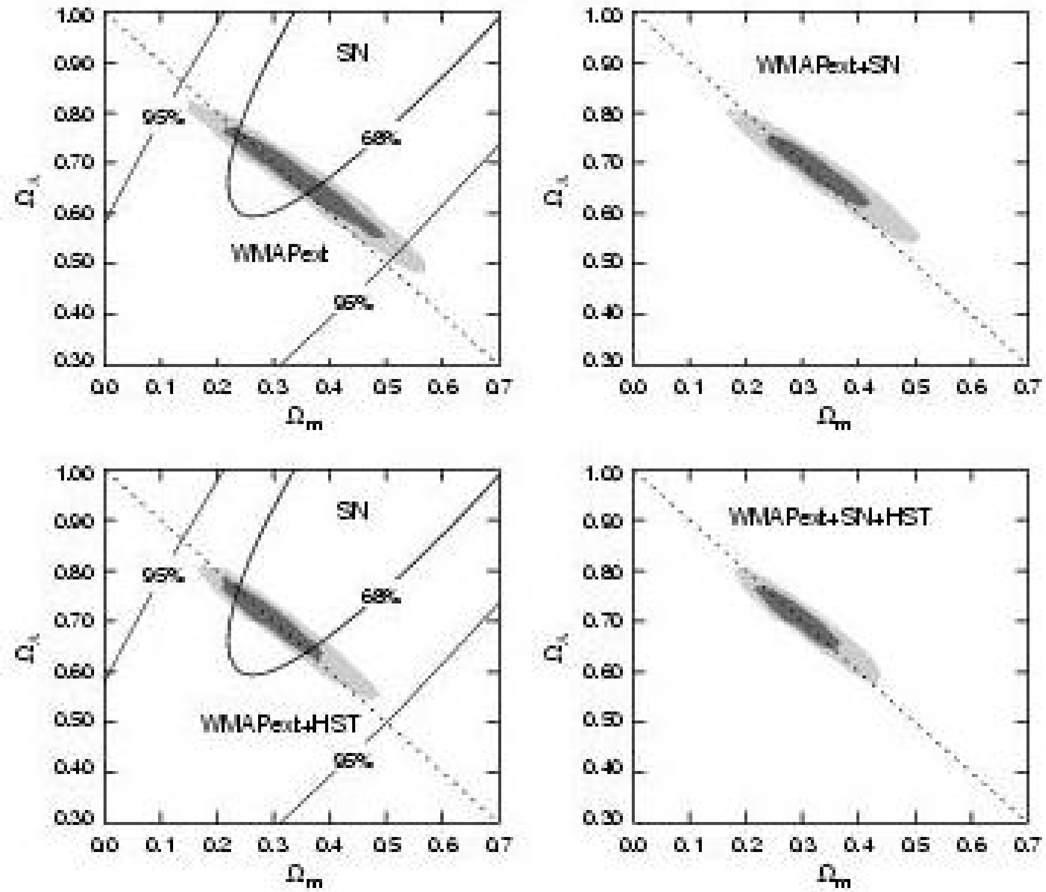
Evidence for Dark Energy: CMB

- Structure of peaks and troughs depends on frequency of oscillation and driving force.
- The CMB is very sensitive to $\Omega_m h^2$



Evidence for Dark Energy: CMB

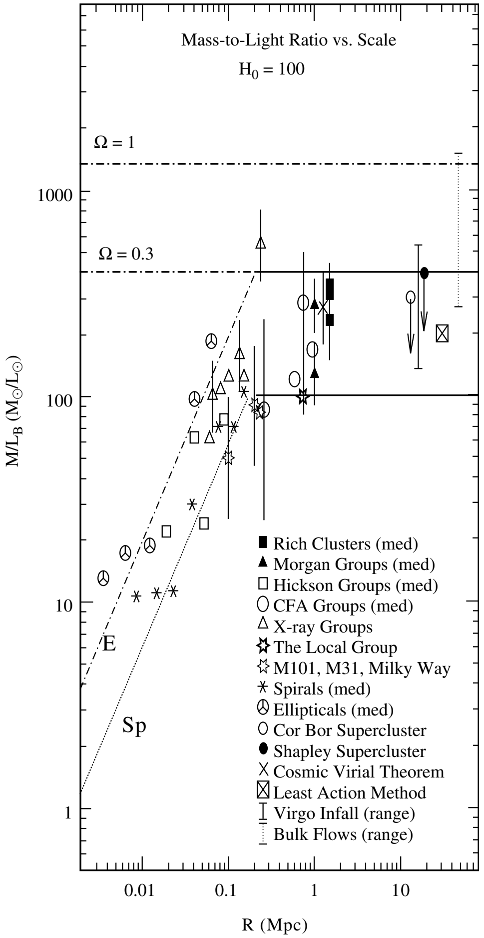
The CMB plus a mild constraint on Hubble constant implies dark energy.



Spergel et al. 2003

Evidence for Dark Energy: Ω_m

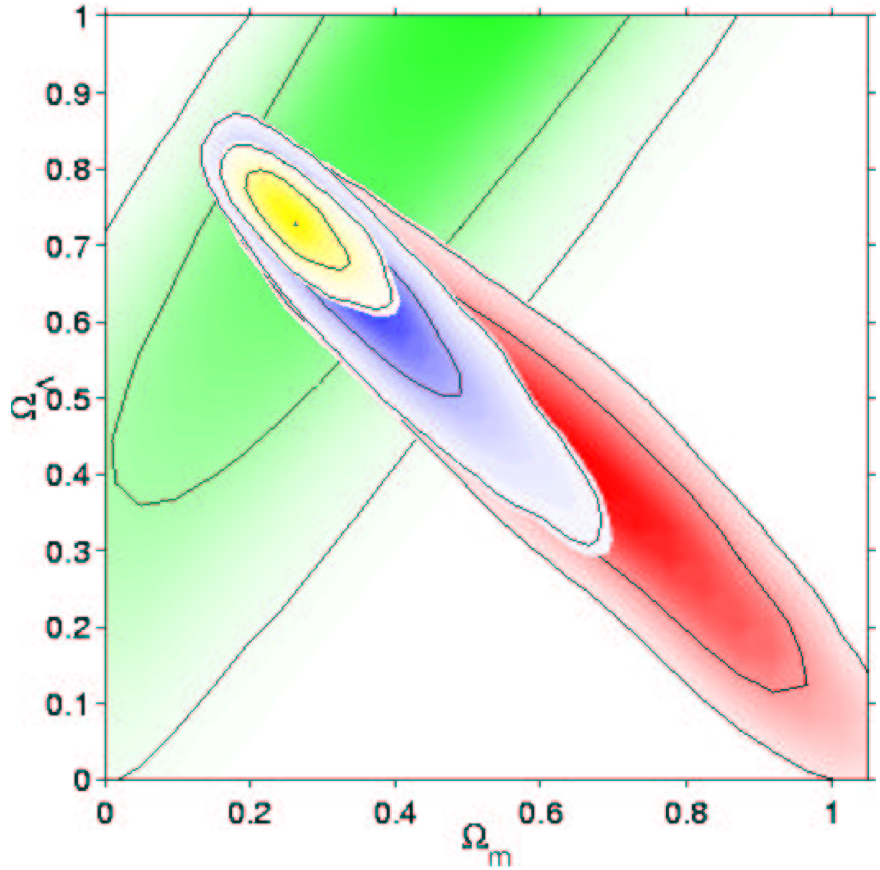
- Direct counting gives $\Omega_m = 0.3$
- Also: Large scale structure, velocities, Clusters . . . All give $\Omega_m = 0.3$



Bahcall et al. 2000

Evidence for Dark Energy

All data agree



SN

CMB

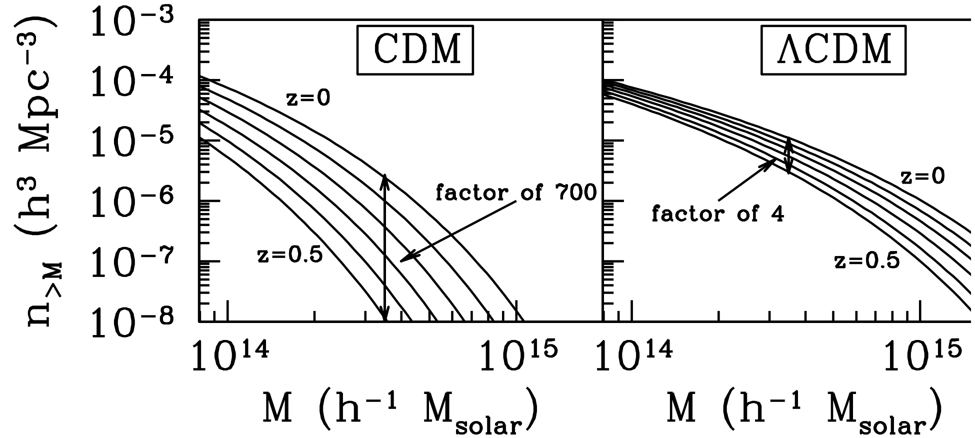
CMB+HST

ALL

Lewis & Bridle 2002

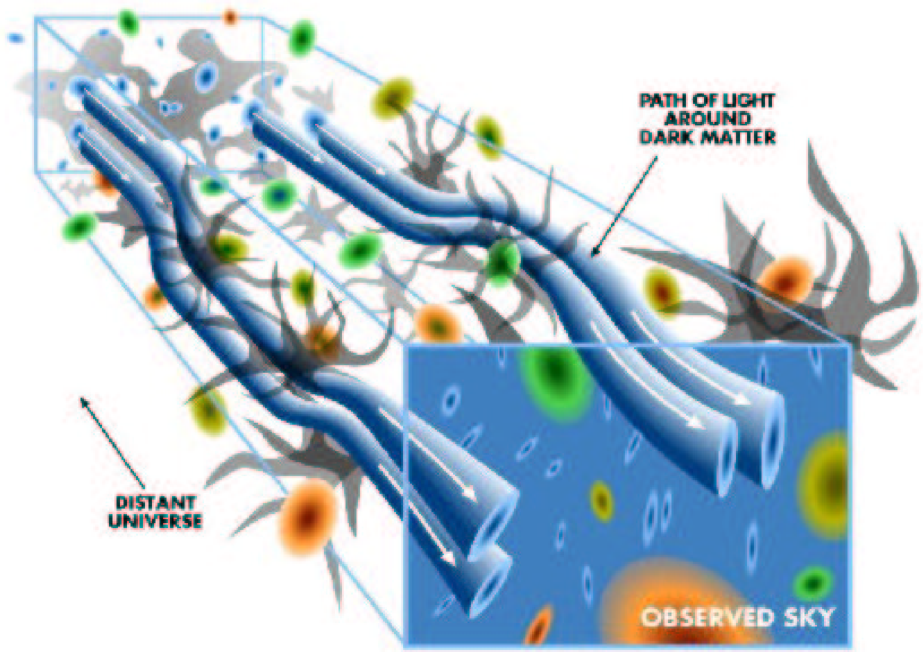
Evidence for Dark Energy: Growth function

- Less growth in a Λ universe
- Clustering was comparable at $z \sim 0.5 - 1$ to now
- Roughly same number of clusters



Evidence for Dark Energy: Growth function

How can we measure mass?

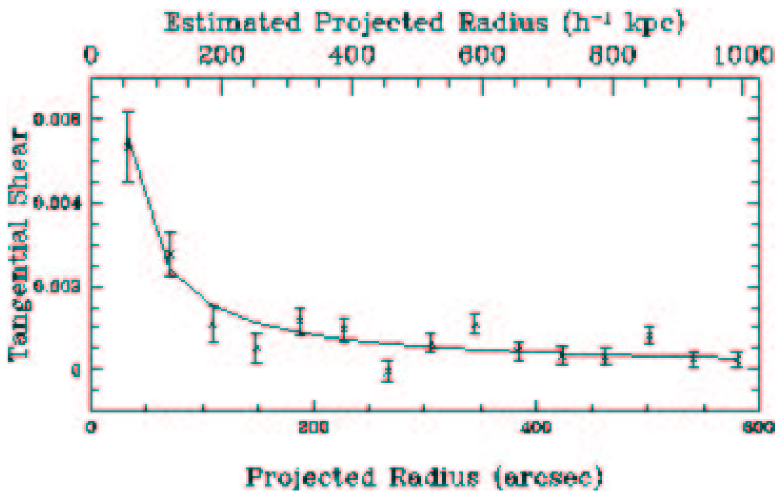


Gravitational Lensing!

Evidence for Dark Energy: Growth function

What can be done with lensing?

- cluster masses
- galaxy-galaxy
- lensing by lss
- lensing of cmb

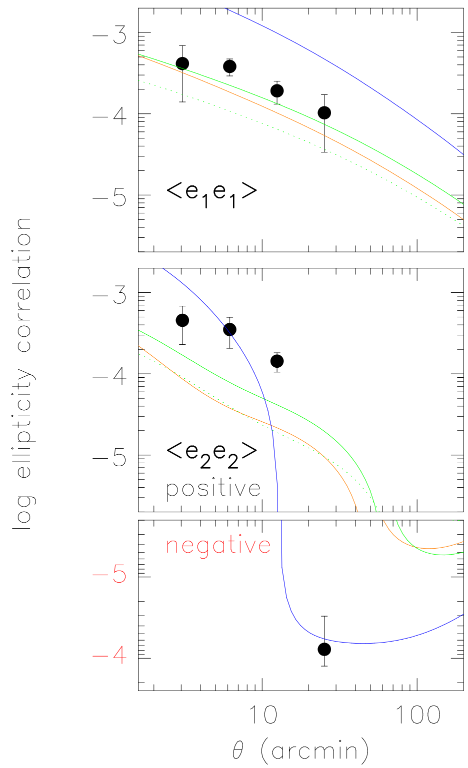


SDSS: Fischer et al. 2000

Evidence for Dark Energy: Growth function

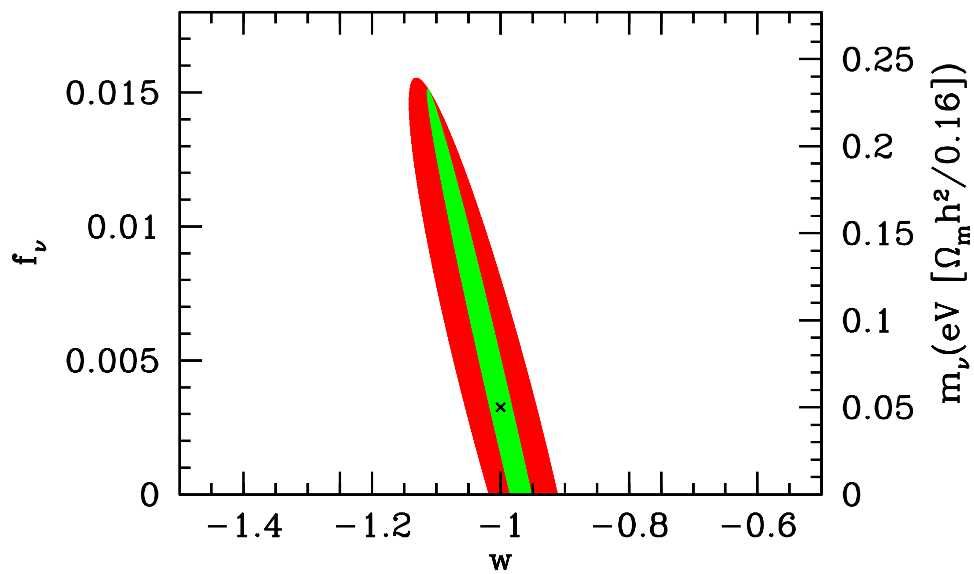
Wittman et al. 2000

- In 2000, four groups detected weak lensing of distant galaxies by large scale structure
- Lensing by LSS today is where CMB was eight years ago



Evidence for Dark Energy: Growth function

- Tomography: Can see how structure grows with redshift
- Growth sensitive to dark energy **and** neutrino mass
- Accelerator ν experiments will teach us about dark energy



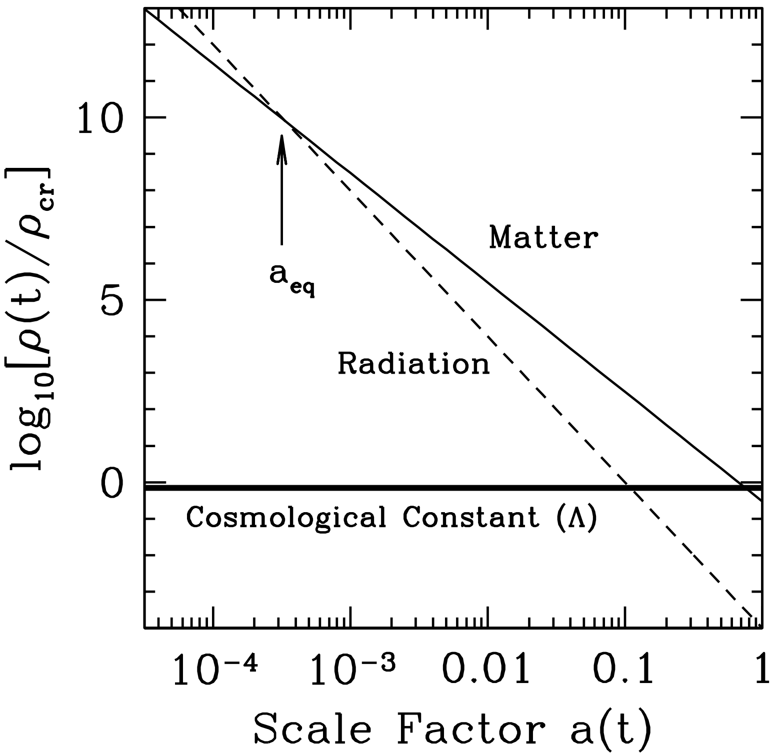
Abazajian & Dodelson, 2003

Niels closed the conversation with one of those stories he liked to tell on such occasions: “One of our neighbors in Tisvilde once fixed a horseshoe over the door to his house. When a common friend asked him, ‘But are you really superstitious? Do you honestly believe that this horseshoe will bring you luck?’ he replied, ‘Of course not; but they say it works even if you don’t believe in it.’”

Heisenberg 1927

What is it?

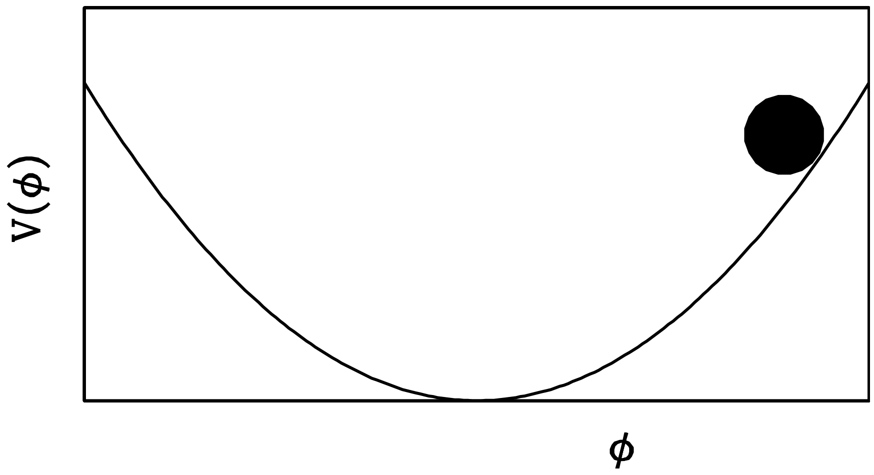
Why now? Now is the only time when $\rho_\Lambda \simeq$ ambient density. Need fine tuning initially to one part in 10^{128} to get present value.



What is it?

Quintessence

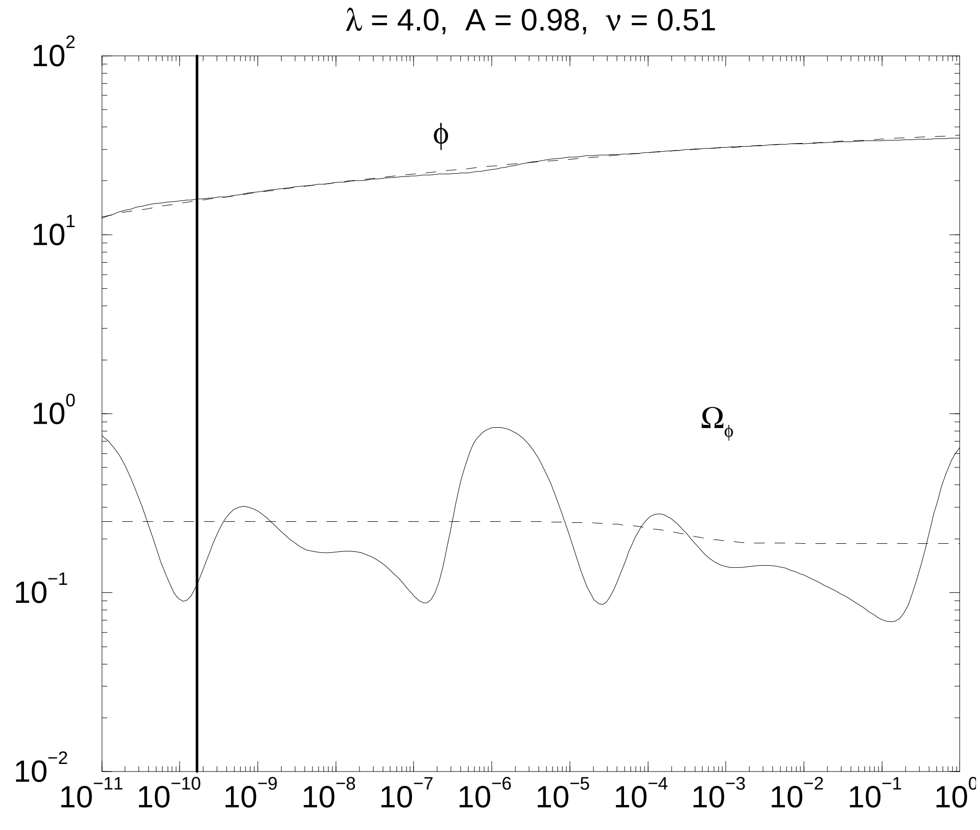
- True value of $\Lambda = 0$
- Some other form of energy non-zero today, will eventually relax to true vacuum.
- Most popular incarnation: single scalar field with $V(\phi)$



What is it?

My (Favorite) Quintessence Model

Exponential potential leads to ρ_ϕ tracking ambient density. Use instead $V(\phi) = e^{-\lambda\phi}[1 + A\sin(\nu\phi)]$



Dodelson, Stewart, & Kaplinghat (2001)

Conclusions

- Several pieces of independent evidence for dark energy: Type Ia supernovae and Cosmic Inventory. Efforts to hunt down systematics and increase statistics are ongoing.

- Another class of evidence growth function (gravitational lensing, clusters) will play a key role in near future

- *Modern Cosmology* encompasses not only smooth universe, but also structure. Need to learn about dark energy, weak lensing, polarization, inflation, galaxy surveys, velocities, clusters, . . .

MODERN COSMOLOGY

Scott
Dodelson

Modern Cosmology begins with an introduction to the smooth, homogeneous universe described by a Friedmann-Robertson-Walker metric, including careful treatments of dark energy, big bang nucleosynthesis, recombination, and dark matter. From this starting point, the reader is introduced to perturbations about an FRW universe: their evolution with the Einstein-Boltzmann equations, their generation by primordial inflation, and their observational consequences. These consequences include the anisotropy spectrum of the cosmic microwave background (CMB) featuring acoustic peaks and polarization, the matter power spectrum with baryonic wiggles, and their detection via photometric galaxy surveys, redshift distortions, cluster abundances, and weak lensing. The book concludes with a long chapter on data analysis. *Modern Cosmology* is the first book to explain in detail the structure of the acoustic peaks in the CMB, the E/B decomposition in polarization which may allow for detection of primordial gravity waves, and the modern analysis techniques used on increasingly large cosmological data sets. Readers will gain the tools needed to work in cosmology and will learn how modern observations are rapidly revolutionizing our picture of the universe.

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Printed in the United States of America

ACADEMIC PRESS

ISBN 0-12-219141-2

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